Motion cueing for 3-, 6- and 8-degrees-of-freedom motion systems

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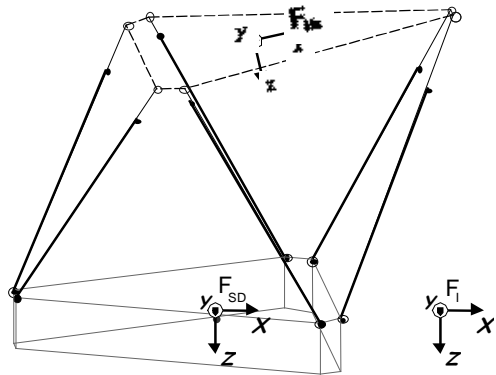martin.fischer@vti.se, hakan.sehammer@vti.se, goran.palmkvist@vti.se

Abstract **–** *Simulators with motion systems are used to give the driver a motion feedback, called motion cue, and thus to increase the realism of the simulation. A motion cueing algorithm defines the movements of the mechanical system based on the current acceleration of the simulator vehicle. The type of the motion system and its related motion envelope is a major factor for the motion cueing which defines both the ability to present certain motion cues as well as their limitations. This paper will describe motion cueing algorithms for three motion system types with a different number of degrees-of-freedom (DOF). The 3-DOF algorithm has been in operation for quite a long time but the described design was not published before, whereas the 6-DOF approach has been reported and this paper gives only an update on the latest results. The motion cueing for the 8-DOF system is newly designed based on experiences with the other two systems. Simulation results promise a high ability to reduce the usage of tilt coordination (common method to present sustained translational accelerations by motion platform tilt, i.e. through gravitational forces) with this system, which a little simplified means to reduce false cues. As new features compared to other algorithms for this type of motion system consequent complementary splitting into low-, mid- and high-frequent signals and cross-system washout compensation are introduced.*

Introduction

Driving behaviour investigations in dangerous traffic situation, human machine interface research or safety system validation take more and more place in driving simulators. Either the respective type of investigations can not be performed in reality for cost, time or ethical reasons or the repeatability of traffic scenarios and overall test conditions as available in simulation is required.

Nomenclature

$\underline{a}_V^{(S)**}$ - vehicle accelerations

$\underline{d}_{MC}^{(I)*}$ - platform displacement
$$d = [x\ y\ z]^T$$

$\underline{f}_V^{(S)*}$ - vehicle specific forces
$$\underline{f} = \underline{a} - \underline{g}$$

$\underline{\beta}^{(I)*}$ - platform orientation
$$\underline{\beta} = [\varphi\ \theta\ \psi]^T$$

$\underline{\omega}_V^{(S)*}$ - vehicle angular velocities

L_{jk} - coordinate transformation from k to j for accelerations
$$j,k \in \{I, Sd, Hx\}$$

T_{jk} - coordinate transformation from k to j for angular velocities
$$j,k \in \{I, Sd, Hx\}$$

CW - classical washout (MCA)

DOF - degree-of-freedom

FTC - fast tilt coordination (MCA)

HP - high-pass filter

LP - low-pass filter

MC - motion cueing

MCA - motion cueing algorithm

TC - tilt coordination

V - vehicle

WO - washout

$\mathbf{F_I}$ - inertial reference frame

$\mathbf{F_{Sd}}$ - sled reference frame

$\mathbf{F_{Hx}}$ - hexapod reference frame

Simulators with motion systems are used to give the driver a motion feedback, called motion cue, and thus to increase the realism of the simulation. A motion cueing algorithm defines the movements of the mechanical system based on the current acceleration of the simulator vehicle. The type of the motion system and its related motion envelope is a major factor for the motion cueing which defines both the ability to present certain motion cues as well as their limitations. This paper will describe motion cueing algorithms for three motion system types with a different number of degrees-of-freedom (DOF).

Motion cueing solutions

3-DOF motion system

The first motion cueing algorithm is designed for a motion system which has the ability to rotate the simulator cabin in roll and pitch directions and to further move it sideways along a linear sled (e. g. VTI Sim2 and VTI Sim3 - Sim3 additionally has a 4-DOF vibration table and the possibility to present yaw (*Nordmark et al., 2004*). The basic algorithm for the presentation of longitudinal acceleration, roll and pitch signals is a variation of the classical washout (*Reid and Nahon, 1985; Fischer, 2009*). The linear sled is mainly used for the presentation of lateral accelerations. To make use of the capabilities of the sled system a road related motion cueing algorithm is implemented which was developed at VTI (Figure 1). An approach reported by *Grant et al. (2002)* is based on the same general idea but is lacking the upper lane-signal feedback loop and it switches between the classical and a road related algorithm instead of combining both into one algorithm as done for the VTI road related algorithm.
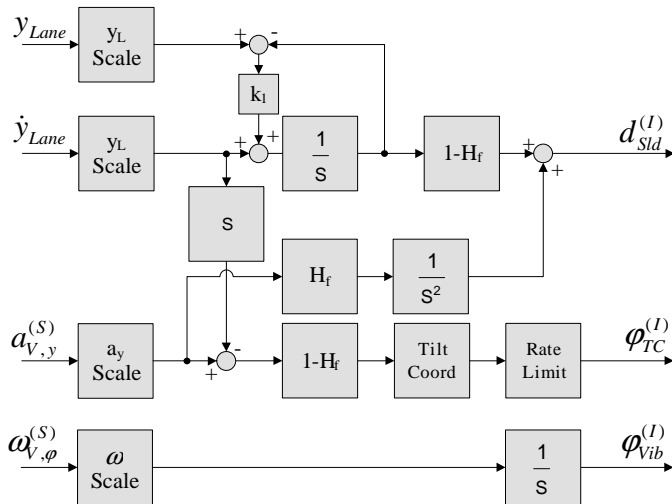

Figure 1. VTI's road related motion cueing algorithm

The main principle of this motion cuing algorithm is to avoid tilting motions caused by lateral accelerations. It is mainly based on the lateral displacement signals y_{Lane} and $\dot{y}_{Lane}$. In the classical washout algorithm the low-frequent lateral accelerations are simulated by a roll rotation (this technique is commonly called tilt coordination). When using the lateral displacement signals the corresponding low-frequent accelerations are introduced by the linear sled instead. Only the difference between these signals and the low-frequent accelerations of the vehicle are presented by roll rotation $\varphi_{TC}^{(I)}$. The usage of the sled system thus reduces the necessary tilt rotations. The high-frequent part of the lateral acceleration is always presented with the sled system. The high-pass

filtered roll velocity of the vehicle is presented separately by the vibration table. Beside the scaling factors, the only tunable parameter is the corner frequency of the high-pass filter ω_0 as it defines as well the characteristics of the low-pass filter $L_f = 1 - H_f(\omega_0)$. This filtering technique (also called complementary filtering) enables an optimal splitting into lower and higher frequencies. The upper lane-signal feedback loop $y^*_{Lane}(t) = \int \left(\dot{y}_{Lane}(t) + k_1 \cdot \left(y_{Lane}(t) - y^*_{Lane}(t) \right) \right)$ ensures a smooth input signal for the sled system, even if the lane position value "jumps". In this case ($\dot{y}_{Lane}(t_0) = 0$) the feedback loop behaves like a first order low-pass filter with k_1^{-1} as the time constant (see transfer function in the frequency domain, given in Equation (1)).

$$Y^*_{Lane}(s) = \frac{1}{s} \cdot k_1 \cdot \left(Y_{Lane}(s) - Y^*_{Lane}(s) \right) \quad \Rightarrow \quad \frac{Y^*_{Lane}(s)}{Y_{Lane}(s)} = \frac{1}{\frac{1}{k_1} s + 1} \tag{1}$$

On straight roads nearly all the lateral acceleration is introduced with the sled system whereas in curves a major part is presented via tilt coordination because here a constant lateral acceleration of the vehicle is present without a lateral movement of the vehicle in relation to the centre line of the road. Depending on the scenario design the motion cueing algorithm can be further adapted to the current situation on-line. A usual parameterization is to use scaling factors between 0.5 and 0.6, a feedback-loop factor k_1 = 1, a 2nd order high-pass filter H_f with a corner frequency of ω_0 = 1.2 and a damping factor of ζ = 0.7.

6-DOF motion system

The most common system for a moving-based driving simulator is a hexapod with its 6 degrees-of-freedom. Different aspects of motion cueing algorithms have been generally investigated and a new algorithm for hexapod systems called fast tilt coordination (FTC – s. Figure 2) had been designed based on these investigations (*Fischer, 2009*). A detailed description of the FTC and the results of a motion cueing evaluation experiment can be also found in earlier publications (*Fischer and Werneke, 2008*; *Fischer et al., 2008*).

The FTC is based on the classical washout algorithm using scaling and filtering techniques and the already mentioned tilt coordination. New features are the consideration of the actually presented high-frequent acceleration $\underline{a}^{(I)}_{WO}$ through a feedback into the tilt coordination path and the avoidance of an additional low-pass filter. This technique has a similar effect as the complementary filtering within the road related MCA. Though, it also takes into account the reduction of the higher frequencies due to the necessary washout filtering. Further, a 6-DOF hexapod motion system enables to choose the point of rotation. The best choice in order to minimize false cues is to use the centre of the drivers head as rotation point. To scale and limit the signal is necessary in order to keep the hexapod within the mechanical restricted motion envelope. This

algorithm introduces higher tilt rotation errors compared to other approaches (e.g. classical washout) due to unrestricted (fast) tilt coordination. However, in an evaluation experiment this turned out to be less important than the achieved reduced timing error (delay between vehicle accelerations and actually presented accelerations).
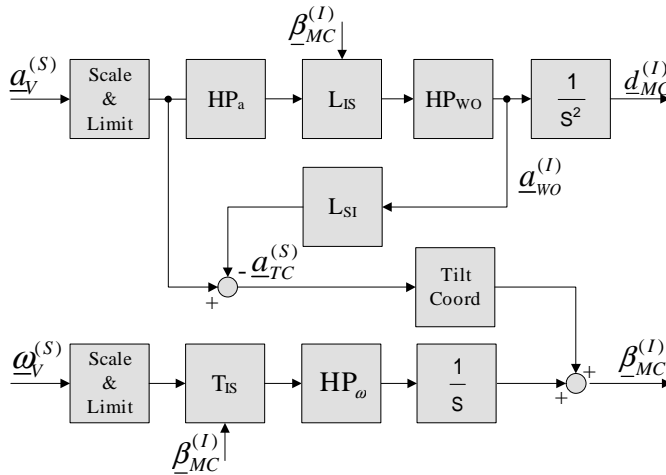

Figure 2. Fast tilt coordination algorithm

The referenced parameterization (*Fischer, 2009*) is to choose scaling factors of 0.5 and damping factors of ζ = 1.0, 1st order high-pass filter H_a with $\omega_{0,x}$ = 2.7, $\omega_{0,y}$ = 2.5 and $\omega_{0,z}$ = 6.0, 2nd order high-pass washout filter H_{WO} with $\omega_{0,x}$ = 0.5, $\omega_{0,y}$ = 0.5 and $\omega_{0,z}$ = 1.0 and 2nd order high-pass filter H_ω with ω_0 = 2.5 for all three DOF.

8-DOF motion system

A more and more often used motion system is a hexapod built on top of a xy-sled (among others the planned VTI simulator Sim4 (*VTI, 2008*), Renaults Ultimate simulator (*Dagdelen et al., 2004*) and the driving simulator at the University of Leeds (*Jamson, 2007*)).This motion system combines the possibilities of a hexapod motion base with the extended motion envelope in x- and y-direction through the sled. Although it can not move the driver in more than the 6 common DOF (surge, sway, heave, roll, pitch and yaw) it is called 8-DOF system, in order to indicate the redundant possibilities of presenting lateral and longitudinal motion. A new algorithm was designed in order to use the full capabilities of this motion system. It is based on both above described algorithms as well as on previous motion cueing experiences. The design varies for the presentation of the longitudinal, lateral and vertical acceleration signals (including the related rotation signals), thus the different DOF will be explained separately. The basic design principle is shown in Figure 3 for the longitudinal accelerations.
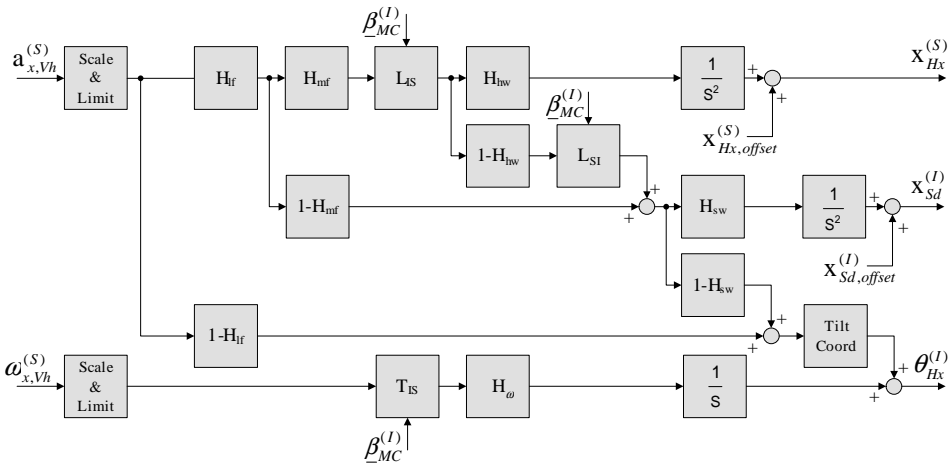
Figure 3. Presentation of longitudinal acceleration and roll velocity with the 8-DOF MCA

As in the road related algorithm, complementary high-pass (H_i) and low-pass filter ($L_i = 1 - H_i$) are used to split the signals. Basically, the high-frequent longitudinal signals shall be presented with the hexapod (upper path in Figure 3), the mid-frequencies with the sled (middle path) and the lower frequencies via tilt coordination. The choice of presenting the highest frequencies with the hexapod instead of the sled was done because of its higher capability of creating onset cues (up to 0.65g and 0.8g/s) and its higher bandwidth (6 Hz cut-off frequency compared to 3 Hz for the sled). The cut-off frequency of H_{mf} determines the separation of high- and middle-frequent signals whereas H_{lf} separates middle- and low-frequencies. The two additional filter (H_{hw} for the hexapod and H_{sw} for the sled system) are used to washout the signals, i.e. to make sure that the motion system always returns to its neutral position. This technique is necessary, though it generates false cues. Hence, it is important to find a good trade-off between the two opposing demands: to use a weak washout (which means a low cut-off frequency) and to return to the neutral position rather quick (which requires a higher frequency) in order to guarantee a bigger motion envelope for the next manoeuvre. However, the remaining high-frequent hexapod washout error will be compensated through the sled motion and the sled washout error will be compensated through the tilt coordination (by cross-coupling the different paths with $1 - H_{hw}$ and $1 - H_{sw}$). The additional offset values for both the hexapod and the sled position allows a pre-positioning of the motion systems according to oncoming events or characteristics of the road ahead.

The motion cueing for the presentation of lateral accelerations has the same basic structure as for the longitudinal signals (see Figure 4). Though, the road related
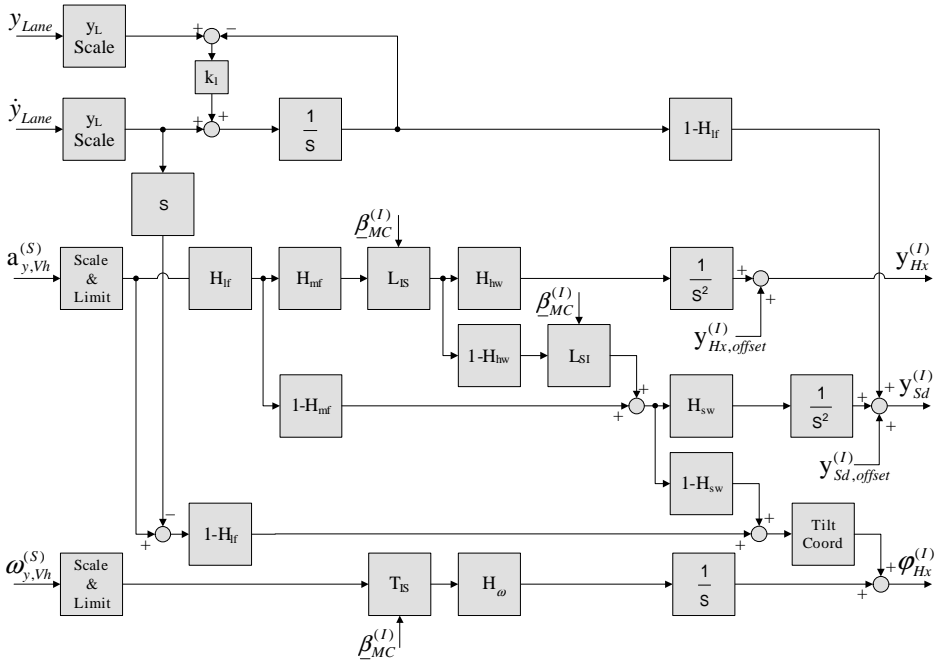
Figure 4. Presentation of lateral acceleration and pitch velocity with the 8-DOF MCA

Signals give an additional input to the sled-system (compare section on 3-DOF algorithm). Hence, the sled-system presents all mid- and low-frequent road related motion and the hexapod is mainly used for the high-frequent acceleration onsets. The tilt-coordination technique is only used for remaining low-frequent signals as sustained accelerations during curve driving.

With the used type of 8-DOF motion system, only the high-frequent vertical accelerations and yaw velocities can be presented. Neither the tilt coordination technique nor some other strategy is available to compensate missing or false cues. Thus the motion cueing for these two DOF is rather simple, as shown in Figure 5.
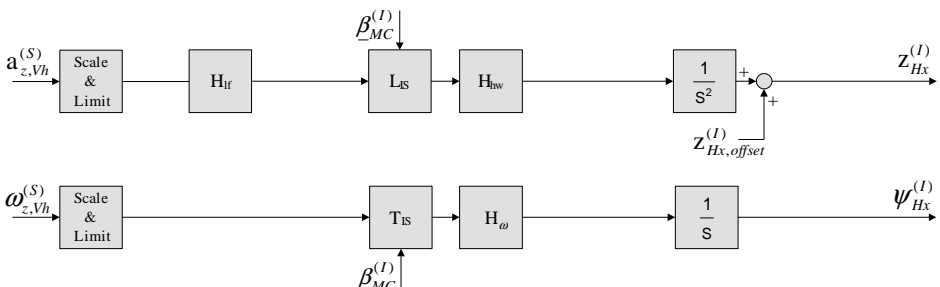

Figure 5. Presentation of vertical acceleration and yaw velocity with the 8-DOF MCA

The simulation based parameter tuning resulted in the following set-up: Scaling factors of 0.5 for all DOF, all necessary damping factors set to ζ = 1.0, 2nd order high-pass filter H_{lf} with $\omega_{0,x}$ = 0.65, $\omega_{0,y}$ = 0.85 and $\omega_{0,z}$ = 1.2, 1st order high-pass filter H_{mf} with $\omega_{0,x}$ = 4.0 and $\omega_{0,y}$ = 6.0, 2nd order high-pass hexapod washout filter H_{hw} with $\omega_{0,x}$ = 0.5, $\omega_{0,y}$ = 0.5 and $\omega_{0,z}$ = 2.0, 1st order high-pass sled washout filter H_{sw} with $\omega_{0,x}$ = 0.1 and $\omega_{0,y}$ = 0.5 and 2nd order high-pass filter H_{ω} with ω_0 = 1.2 for all 3 DOF.

A similar approach, combining a classical washout based algorithm with the lane-based algorithm presented by *Grant et al.(2002)*, has been already introduced by *Chapron and Colinot (2007)*. However, there are some main differences between their approach and the here presented 8-DOF algorithm: *Chapron and Colinot* chose to use non-linear scaling factors and variable tilt velocity limitation in order to avoid false cues as much as possible. With the here described approach, the same goal shall be achieved through cross-system compensation and a parameterisation that avoids tilt coordination as much as possible. Another algorithm presented by *Grant et al. (2006)*, does not include a lane-based approach but is designed for a motion system which also combines a hexapod with a xy-sled motion system (the NADS simulator). Though, the NADS system further comprehends a yaw turntable and a cab vibration system (as well as a larger stroke in x and y which does not imply any principle difference for the motion cueing algorithm but has a huge influence on the parameter tuning options). Although both algorithms include some similar principles (e. g. using vehicle accelerations as input signals instead of specific forces, (partly) similar frequency splitting strategy, rate limit above 3 deg/s) some bigger differences can be noticed as well (e. g. consequent splitting into low-, mid- and high-frequent signals and washout compensation with the VTI approach vs. hexapod tilt coordination related to turntable position). The extended NADS motion system enables different motion cueing options just as it includes some additional design needs (as the necessity to relate the tilt angle to the yaw table position). Thus a complete design comparison of the two algorithms is not feasible.

Results

For the comparison of the described algorithms different acceleration characteristics are used: a full throttle and a moderate acceleration phase for the longitudinal direction and steering maneuvers on a straight road and during curve driving for the lateral direction. The following figures show only the results for the 6-DOF and the 8-DOF algorithm, as the main motion cueing signal characteristics of the 3-DOF approach is similar to the 6-DOF for longitudinal accelerations and similar to the 8-DOF for lateral accelerations (except for the high-frequent hexapod motion).Figure 4 shows the contributions of the different motion cueing techniques and motion systems to the presentation of the acceleration signal for both, full throttle acceleration and a more moderate acceleration during driving.
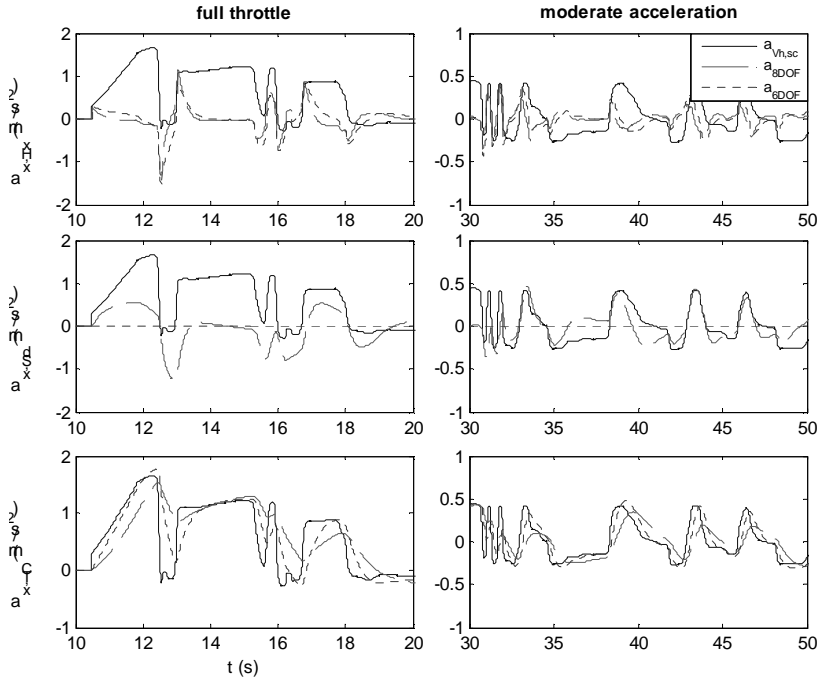
Figure 4. Full throttle and moderate longitudinal accelerations; Signal presentation split between translational hexapod motion (up), sled motion (middle) and tilt coordination (low)

The resulting high-frequent accelerations presented with the hexapod do not differ very much between the two compared approaches. However, the usage of a sled system clearly reduces the necessary tilt coordination. So the 6-DOF approach generates tilt rates up to ±20 deg/s, whereas the maximum tilt rate with the 8-DOF algorithm is ±10 deg/s during full throttle and strong braking maneuvers and less than ±4 deg/s for moderate accelerations. The same effects as for longitudinal acceleration presentation can be observed when looking at the different signals during steering actions (see Figure 5).

The difference between both approaches is even more obvious as here the biggest part of the lateral accelerations is presented with the sled when using the 8-DOF system. Thus, the high frequent hexapod accelerations are noticeable smaller compared to the 6-DOF approach and tilt coordination is nearly completely avoided on straight roads and only used for the very low-frequent, sustained part of the acceleration during curve driving. So, the difference in tilt velocities is even bigger than for the longitudinal accelerations: more than ±20 deg/s for the 6-DOF algorithm (peaks up to 30 deg/s) compared to less than ±2 deg/s on straight roads and less than ±5 deg/s on a curvy road for the 8-DOF approach.

The combination of the two, respectively three signals resemble the scaled vehicle accelerations very well for all discussed approaches (shown for the 6-DOF and the 8-DOF algorithm in Figure 6).
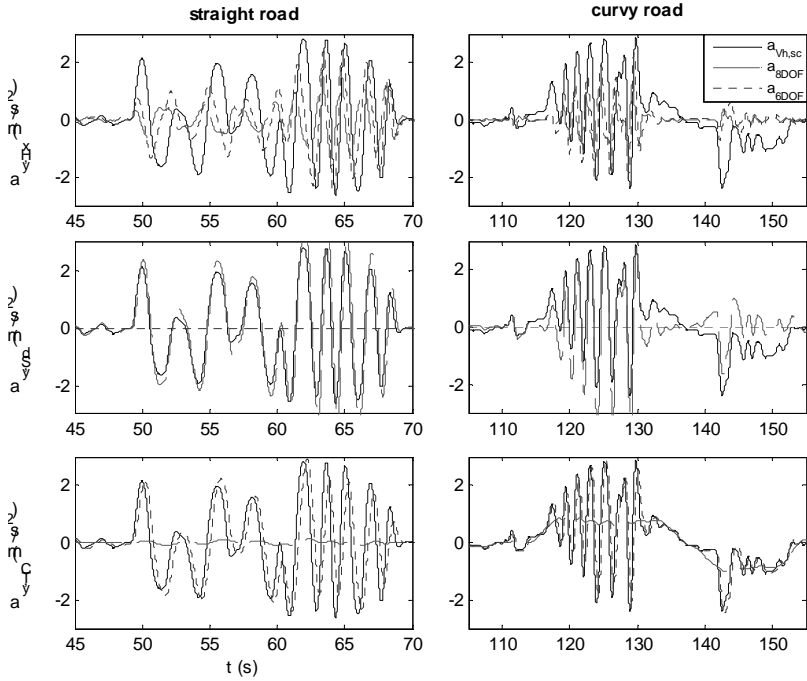
Figure 5. Lateral accelerations on a straight and a curvy road; Signal presentation split between translational hexapod motion (up), sled motion (middle) and tilt coordination (low)
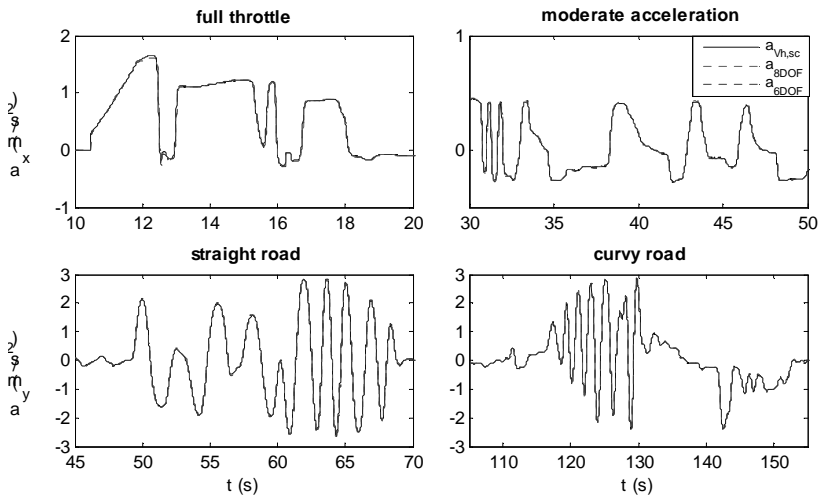

Figure 6. Scaled vehicle accelerations compared to the resulting output signals generated by the 6-DOF and the 8-DOF motion cueing algorithm for different types of roads and manoeuvres

Discussion

Three motion cueing algorithms designed for different motion systems (3-, 6- and 8-DOF) have been explained. All shown results are based on simulations. However, the first two (3- and 6-DOF) are currently used and approved algorithms and the simulation for the 8-DOF approach takes the actual system limits into account (i.e. motion envelope, maximum velocities and accelerations of the different motion systems) and is based on the experiences with the first two algorithms.

The motion cueing algorithm for the 3-DOF motion system (pitch, roll and y-sled) provides a very good lateral motion feedback, though it lacks the possibility to present strong high frequent longitudinal accelerations and the rotation point is fixed. The shown algorithm for a common 6-DOF hexapod has this opportunity, to use a specified rotation point like e.g. the drivers head and it has a general flexibility to vary the motion cueing strategy according to a given task. However for manoeuvres with a higher dynamic, the necessity to use tilt coordination is immense. Even though it has been shown in the past that this type of motion system is well accepted (at least by non test-drivers) and thus can be very well used for certain types of simulator experiments, the reduction of false cues due to tilt coordination increases the immersion and enables a realistic feedback even for those manoeuvres with higher dynamic demands. This opportunity is provided by 8-DOF systems with linear sleds. They combine the advantages of both above mentioned systems and enable a good reduction in the usage of tilt coordination.

The performance comparison of the three described algorithm as well as previous experiences with the different systems leads to the following general design principles:

1. Avoid tilt coordination as long as possible.

2. If tilt coordination is inevitable, tilt without (or at least a quite unrestrictive) rate limit in order to avoid time lags in signal presentation. Use the drivers head as tilting point.

The mentioned road related motion cueing is clearly one possibility to reduce tilt coordination; the usage of the motion washout technique (i.e. to bring the simulator back into its neutral position) can be another, because it enables a bigger flexibility in presenting motion feedback to fast and unpredictable vehicle movements (independent of the direction of the motion). However, as it can cause false cues (depending on the chosen washout parameter) a weak washout is generally preferable. If redundant cueing options are available (e.g. for lateral acceleration) this leads to the following washout design rules:

1. Chose filter parameter such that the need to washout signals is reduced (i.e. a hexapod has a greater need for a washout than a sled system).

2. Chose a small washout frequency (equals a weak washout).

3. Compensate the washout with another motion system or cueing technique (e. g. tilt coordination) if feasible.

However, there are some open questions which have to be addressed with tests using the real system:

1. What is the best balance between the tilt error (when tilting with a tilt velocity higher than the perception threshold) and false cues due to time lags in the signal presentation (when using strict tilt rate limits) for vehicle signals with huge step-like acceleration changes (e.g. due to an emergency brake)?

2. Is washout compensation always wanted? Can it lead to noticeable counter movements of the hexapod vs. the sled system (e.g. a fast sled move compensated by a fast hexapod move into the opposite direction can theoretically keep the body in place, though practically it can lead to perceivable accelerations or jerks due to the different dynamic characteristics of the different motion systems)? Depending on the road course it maybe is not even necessary to washout a position signal because the current simulator position serves better as a starting point than the neutral position (e.g. during an overtaking manoeuvre)?

3. Another major concern according to the 8-DOF motion system is the introduced false cue when moving the sled system while tilting the hexapod at the same time (i.e. lateral acceleration is not presented exactly in the drivers lateral direction), as done during curve driving (see Figure 5, right). Is this effect perceivable? And if yes, how severe is it experienced, i.e. does it reduce the immersion strongly?

Although simulation results as well as experiences with the described 3-DOF motion cueing approach indicate that the mentioned lateral false cue generally should not have a strong effect on the motion perception, this has to be verified within the 8-DOF system.

After first experiences with the real system the presented strategy will be improved, taking published ideas and experiences as well as the first evaluation results into account. A possible enhancement could be to use an adaptable washout and pre-positioning (especially for the presentation of longitudinal accelerations), to test a vehicle speed and/or simulator position dependent algorithm or use a strategy without fixed filter-frequencies (e.g. adaptive optimal control with frequency-dependant scaling factors (*Tajima et al., 2006*) or tilt limiter settings adapting to linear acceleration levels (*Chapron and Colinot, 2007*). The role of false cues produced through sled movements while the hexapod is tilted (as mentioned above) will be explored as well. Further, the scientific discussion is still ongoing under which conditions the motion perception threshold is at which level (see e.g. *Wentink et al., 2008; Chapron and Colinot, 2007; Nordmark, 1994*) and which perceivable false cues are acceptable when using the tilt coordination method (*Fischer, 2009*).

All these open questions can not be answered by pure computer simulations as the main goal is to create a good illusion of driving a real car, which has to be experienced and finally evaluated by test drivers in the real simulator. Thus, these questions will be (as much as possible) addressed during the initial phase of the new system in order to evaluate the already achieved level of fidelity and to reveal necessary enhancements. However, based on the simulation results, the

developed algorithm and the according parameter choices seem to be a good starting point for the evaluation runs.

Keywords: Design and architecture, motion rendering

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